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DETERMINISTIC AND STOCHASTIC ASPECTS OF CONSTRUCTED WETLAND PERFORMANCE AND DESIGN

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ABSTRACT

Potato processing wastewater contains high concentrations of COD, TSS and TKN. A combination of surface flow wetlands, intermittent vertical flow wetlands, ponds and land application has been used for treatment. This engineered natural system balances irrigation requirements, nitrogen supply and seasonal growth patterns to provide effective year-round operation. A first pilot wetland was operated to determine operability, effectiveness, and plant survival at high COD and nitrogen concentrations. A second pilot system of four wetlands in series was operated to obtain design and operating information. Two surface flow wetlands provided TSS and COD reduction, and ammonified the organic nitrogen. Subsequently, nitrification occurred in the vertical flow wetlands, followed by denitrification in a surface flow wetland. The design target was a balanced nitrogen and irrigation supply for application to crops. Winter storage as used to match the crop application period to the growing season. Both pilot projects met design objectives, and a full scale system has begun operation.

KEYWORDS

Constructed wetlands, design, deterministic modeling, Monte Carlo modeling, wastewater, stochastic processes, parametric variation, temperature, season, depth, hydraulic loading.

INTRODUCTION

The design and description of treatment wetlands involves two principal features: hydraulics and pollutant removal. Previous literature utilizes concepts of Darcian flow in subsurface flow wetlands (SSF)(Hobson, 1989; Fisher, 1990), and of vegetated open channel flow in free water surface wetlands (FWS)(Hosokawa and Horie, 1992). Previous literature suggests first order, irreversible pollutant reduction removal models for treatment wetlands. First order models may be either area-specific, and thus determine the necessary wetland acreage (Schierup et al., 1990; Mitsch et al., 1995; Upton and Green, 1995) or volume-specific, and thus determine the wetland water volume (USEPA, 1993). These current paradigms are deterministic, meaning that the equations purport to represent the wetland output concentrations in response to inlet concentrations, flow rate, and area or volume. However, wetland performance also includes a good measure of variability that is not predicted by the average values of these forcing variables. That variability is caused by unpredictable events, such as the fluctuations in input flows and concentrations, and by changes in internal storages, as well as by weather, animal activity and other ecosystem factors.

More complex models may be contrived, to include dynamic behavior of the various ecosystem compartments and processes (Kadlec, 1996), but these require very large amounts of data for proper calibration. Input/output

(I/O) data on flows and concentrations are generally insufficient for calibration, and consequently little is known in general about the numerous model parameters. It may be presumed that calibrated compartmental models will provide more details of internal allocations of chemicals, but it is not clear that more detailed deterministic models will provide more accurate descriptions of overall wetland performance. At this point in the evolution of treatment wetland technology, only simple models can be calibrated for most operational systems. However, expanding intersystem databases provide the opportunity to examine the assumptions inherent in current models. This paper examines the current design frameworks, to provide further insights on their uses and limitations.

HYDRAULICS

Deterministic Steady State Calculations

The hydraulic profile of the constructed wetland is required, to ensure that depths and head loss are within project constraints. Hydraulic calculations involve three principal components: an energy/momentum equation, the water mass balance equation, and the boundary conditions on flow and depth. Wetland flows are almost always gradually varied, so the momentum equation reduces to the requirement that friction be balanced by head loss. However, flow rate, depth and water surface slope are all potentially spatially variable, and so require all three principal components. Large treatment wetlands, and those with complicated or irregular geometries, may necessitate the use of either one- or two-dimensional computer codes, such as HEC2 or SHEET2D™. These programs return local values of depth and flow over the entire expanse of the wetland. In many cases, there is a simple one-dimensional geometry. For both SSF and FWS wetlands, the water mass balance is:

$$Q = Q_i + W x (P - ET) = u W h \tag{1}$$

and the boundary conditions are:

$$h(x = L) = h_o \qquad Q(x = 0) = Q_i \tag{2,3}$$

The friction equation may be generalized to:

$$u = a h^{b-1} \left(- \frac{d(B+h)}{dx} \right)^c \tag{4}$$

a,b,c	= constants	P	= precipitation, m/d
B	= bottom elevation, m	Q	= water flow rate, m^3/d
h	= free water depth, m	Q_i	= inlet water flow rate, m^3/d
ET	= evapotranspiration, m/d	u	= superficial velocity, m/d
h	= free water depth, m	W	= wetland width, m
h_o	= free water depth, m	x	= distance from inlet, m
L	= length of wetland, m		

Manning's equation for turbulent open channel flow corresponds to a = 1/n, b=2/3 and c=1/2. For FWS wetlands, $1 \leq b \leq 2$ and $0.7 \leq c \leq 1.0$ (Kadlec, 1996). For Darcian flow in SSF wetlands, $a=k_e$, b=1 and c=1. Hydraulic profiles require simultaneous solution of (1)-(4). In many cases, flows are distance-thinning or distance-thickening; characterized by non-constant depth (Hobson, 1989; Kadlec and Knight, 1996). Velocity may also be distance-variable, in response to P-ET; or to bed slope or exit weir setting.

Time Series and Stochastic Contributions

Atmospheric contributions to the wetland water budget cause temporary deviations from the steady state conditions computed from (1) - (4). Evapotranspiration occurs during daytime, and may be suppressed during cloudy, rainy periods. Rainfall occurs on a schedule described by frequency distributions of intensity, duration and inter-event spacing. Inlet wastewater flows may also be subject to daily, weekly and seasonal variation, as well as random upsets. These stochastic events are important, because they lead to variations in detention time, and to dilution or concentration of dissolved species during transit. They may also threaten the hydraulic integrity of the system, by causing flooding or dryout conditions. Hydraulic design should include consideration of high and low flow extremes, as well as the extremes of atmospheric additions or losses. There are also significant implications for pollutant reduction, as discussed below.

POLLUTANT REDUCTION

Deterministic Steady-State Models

Design often contemplates a stable period of operation, over which input and outputs are averaged. The rate and temperature equations are of the form:

$$J = k(C - C^*) \qquad R = k_V(C - C^*) \qquad (5,6)$$

$$k = k_{20}\,\theta^{(T-20)} \qquad k_V = k_{V20}\,\theta^{(T-20)} \qquad (7,8)$$

C = concentration, mg/L
C^* = background concentration, mg/L
J = areal removal rate, gm/m^2/yr
k = areal removal rate constant at T °C, m/yr
k_{20} = areal removal rate constant at 20T °C, m/yr
ε = porosity, -
k_V = volumetric removal rate constant at e T °C, 1/d
k_{V20} = volumetric removal rate constant at 20 °C, 1/d
R = volumetric removal rate, gm/m^3/d
T = temperature, °C
θ = temperature coefficient, -

The two alternate rate constants are related by the free water depth, with $k = (\varepsilon h)k_V$, usually together with a change in time scale from years to days. The rates (5) or (6) are used in combination with the water mass balance (1) to obtain pollutant concentration profiles. If flow is plug flow, with constant (P=ET), exponential profiles are predicted (reaching a plateau of C=C*):

$$\frac{C - C^*}{C_i - C^*} = \exp[-ky/q] = \exp[-k_V \tau y] \qquad (9,10)$$

q = hydraulic loading rate, m/yr
y = fractional distance through wetland, =x/L
τ = nominal detention time, d

However, if flow varies due to α = P-ET ≠0, then power law profiles are predicted:

$$\frac{C - C'}{C_i - C'} = \left(1 + \left[\alpha y/q\right]\right)^{-\left(1 + k/\alpha\right)} \qquad (11)$$

$$C' = C^* \left[\frac{k}{k + a}\right] \qquad (12)$$

Evapotranspiration (rain) has two effects: lengthening (shortening) of detention time, and concentration (dilution) of dissolved constituents. The use of (9,10) with an average flow rate compensates for altered detention time, but not for dilution or concentration. The fractional error due to flow averaging is approximately equal to α/q, for $\alpha/q > -0.5$. Thus, if 25% of the inflow evaporates, use of (9,10) with average flow predicts concentrations 25% lower than required by the mass balance. If rain adds 25% to the flow, use of (9,10) predicts concentrations 25% higher.

If the hydraulic efficiency of the wetland in design is less than that in the data sets that generated the rate constants, as indicated by more mixing or short-circuiting, then corrections for the degree of non-ideality should be applied (Kadlec and Knight, 1996).

Kadlec and Knight (1996) surveyed information from many FWS and SSF wetlands treating domestic wastewater, and determined the central tendencies for areal rate constants, background concentrations, and temperature factors (Table 1). In the case of nitrogen species, the rate constants are for the sequential conversion processes, and not for system inputs and outputs. Considerable intersystem variability was found, as might be anticipated from the large variability in wetland characteristics. The designer should modify values in Table 1 according to the specifics of the intended wetland.

Table 1. Rate constants, background concentrations and theta factors.

	Surface Flow			Subsurface Flow		
Parameter	k_{20} ,m/yr	C*, mg/L	θ	k_{20} ,m/yr	C*, mg/L	θ
BOD	34	3+	1.00	180	3+	1.00
TSS	1000	5+	1.00	3000	7+	1.00
TN	22	1.5	1.05	27	1.5	1.05
TP	12	0.02	1.00	12	0.02	1.00
FC	75	50+	1.00	95	10+	1.00

Parametric Variability

The parameters of the first order models are referred to as "rate constants," but there is no *a priori* reason to believe that these "constants" do not in fact depend upon other operational characteristics of the wetland. Inter-system variability and intra-system stochastic effects are to be anticipated. However, the design variables of depth and hydraulic loading, which combine to determine nominal detention time, are directly involved in sizing computations. If k-values change with depth and flow rate, then those effects must be accounted in design.

Depth. The relation $k = (\varepsilon h)k_V$ requires that both k and k_V cannot be independent of depth. If k_V is constant with respect to depth, then k is proportional to depth. This condition requires chemical reaction to be uniformly distributed vertically throughout the water column. If k is constant, then k_V is inversely proportional to depth. This condition corresponds to chemical reaction apportioned to wetland surface area. Neither ideal extreme is likely to be present in a treatment wetland, but data show FWS wetlands to behave with constant k, not k_V. For instance, the reduction of total nitrogen (TN) in 17 wetland cells at Jackson Bottoms, OR (SRI, 1990) shows k_V inversely proportional to depth (Fig. 1).

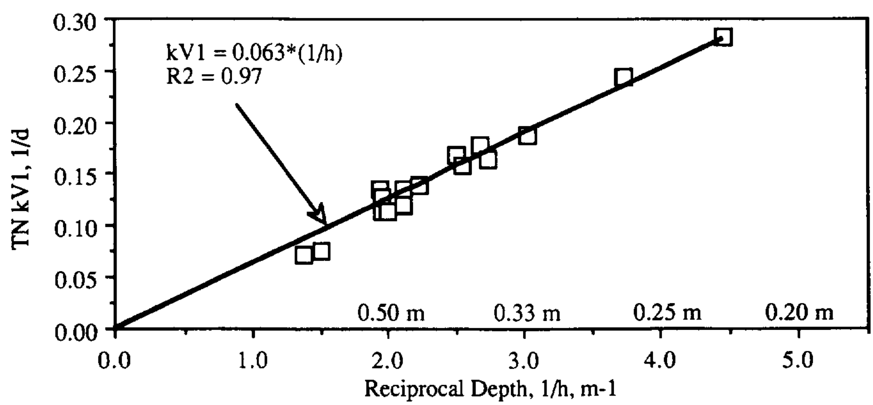

Figure 1. Depth effect on the Jackson Bottoms TN rate "constant".

The implications for design are very important. If the volumetric model is utilized in FWS calculations, there appears to be the option of increasing performance by increasing the water depth, and hence increasing the nominal detention time. That advantage is lost if the volumetric rate "constant" decreases with increasing depth. Table 2 illustrates this effect for the side-by-side tests at Arcata, CA (Gearhart, et al., 1983). The rate constants in Table 1 are determined for C*=0, and are designated k_{V1}, indicating a one-parameter rate model.

Table 2. Arcata BOD rate "constants" vs. depth.

Flow m^3/d	Depth m	% Increase in HRT	BOD Rate Constant, 1/d	% Decrease in k_V
93	0.40		0.29	
94	0.55	37	0.17	42
86	0.36		0.25	
83	0.61	76	0.13	49
45	0.30		0.28	
49	0.49	49	0.14	48
29	0.33		0.14	
29	0.53	78	0.08	40
23	0.35		0.14	
24	0.50	39	0.09	36

The situation for SSF wetlands is less clear, because there are fewer data available. Preliminary reports from a side-by-side study at Baxter, TN indicate that k_V may be more constant than k for BOD (George et al., 1994), but that the reverse is true for TN rate "constants."

Hydraulic loading. One parameter k-values are strongly dependent on hydraulic loading rate, as illustrated by the data from Danish soil based wetlands (Schierup et al., 1990) (Fig. 2). This is in part due to the existence of background concentrations, which create this effect in I/O data analysis; and in part due to mechanistic influences within the ecosystem, such as mass transfer velocity dependence.

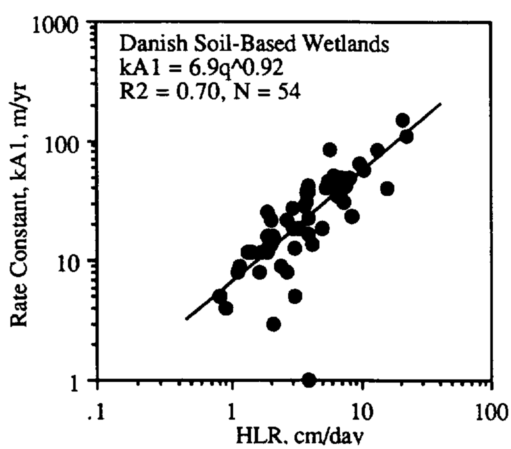

Figure 2. HLR effect on BOD rate constant.

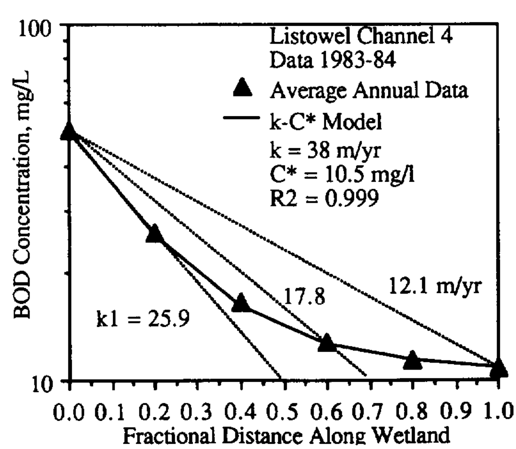

Figure 3. BOD rate constants from I/O data.

As the effluent point of the treatment wetland moves further out along the C* plateau, the k1-value, determined as the slope of the logarithmic model, becomes smaller (Fig. 3). As a result, k1 or kV1 are proportional to hydraulic loading rate to a power, $k \propto q^m$. For example, data from 55 SSF wetlands for BOD shows $k_V1 \propto q^{0.63}$; data from 47 FWS wetlands for BOD shows $k_V1 \propto q^{0.79}$. This effect is not as large for pollutants with very low values of C*, or if reduction is not close to C*. This loading dependence, together with the depth dependence discussed above, indicate that the one parameter version of equations (9,10) should more properly read:

$$\frac{C}{C_i} = \exp\left[-k_1' y / q^{1-m}\right] = \exp\left[-h k_{V1}' \tau^{1-m} y\right] \quad (13,14)$$

Temperature. Many individual biological processes have temperature sensitive rates, and consequently the rate constants that represent the consortia of wetland processes may also be temperature sensitive. However, the overall reduction of a pollutant typically involves an intricate web of transfers and transformations, which involve physical processes such as sedimentation and sorption, microbially mediated storages and conversions, uptake and storage in biota of varying sizes and life histories, and transfers of other reactants, such as oxygen and carbon dioxide. Some processes, and some incoming flows and concentrations, are seasonally variable, and those influences may become confused with temperature effects. This complexity indicates that ecosystem data is the only sure source of information on the influence of temperature on wetland pollutant reductions.

Table 1 shows that ecosystem nitrogen species reaction rates slow at lower temperatures, but that there is not a temperature effect on TSS removal. In contrast to these intuitive results, wetland data indicate no temperature effect on BOD, total phosphorus (TP) and fecal coliform (FC) reductions. Of these, the non-effect for BOD is somewhat counter-intuitive, and deserves further discussion. Some wastewater treatment technologies show significant lowering of BOD k-values as temperature is lowered, notably suspended growth processes and aerated lagoons (Metcalf and Eddy, 1991). The most relevant companion technologies are overland flow and facultative lagoons, which show little temperature change in BOD reduction (Table 3). Of equal importance is the fact that the inclusion of a temperature coefficient in data analysis accounts for very little of the variance in data. For instance, including a theta factor in the FWS data (Table 3) accounts for only 6.6% of the variance.

Table 3. Theta factors for BOD for natural systems technologies.

FWS Wetlands		**SSF Wetlands**	
Listowel, ONT (5 wetlands)	0.930-1.011	Richmond, NSW (3 wetlands)	0.915-0.972
Arcata, CA (12 wetlands)	0.97-1.01	Snogerod, SWE	1.003
Orlando, FL	0.976	Mühlen, AUS	1.006
Columbia, MO	0.980	**Overland Flow**	
Wetwang, UK	0.973	Data from 3 studies	1.000-1.019
Richmond, NSW	0.913	**Facultative Lagoons**	
Brookhaven, NY	0.991	Data from several lagoons	0.962-1.015
Ouray, CO	1.019		

Time Series: The Unsteady State

Startup. Constructed wetlands typically require a few months for vegetation and biofilm establishment, and one to two years for development of the litter compartment. Leaching or sorption of some constituents may also occupy a period of a year; or more if a SSF media has been selected for sorption capacity. The simple models given above do not necessarily apply during this period.

The input-output lag. Detention times in constructed wetlands are often in the range of 7 - 10 days, and may be as long as three or four weeks. Plug flow design equations would theoretically relate current outflow concentrations to inflow concentrations one detention time earlier. However, tracer studies indicate significant blurring of the exit response, with some elements of water leaving after three or more detention times. Design equations should not be applied over periods shorter than three detention times, so that outputs may reflect input conditions appropriately.

Input-output tracking. Fluctuations in internal wetland storages, and mechanistic variability, preclude the use of the simple design models on a short time step, even if the transport lag is taken into consideration. Even large, slow changes in inputs do not necessarily produce similar trends in outputs. Figure 4 shows an example time series together with the first order model result. The model was calibrated to produce the correct average outlet concentration for the two year period. On a short time scale, the deterministic design model predicts direct responses to inlet peaks and valleys, but the data do not reflect such behavior. The detention time in this wetland was about six days. Predictions were sometimes consistently low for a few months (spring, 1981); and sometimes consistently high (spring, 1982).

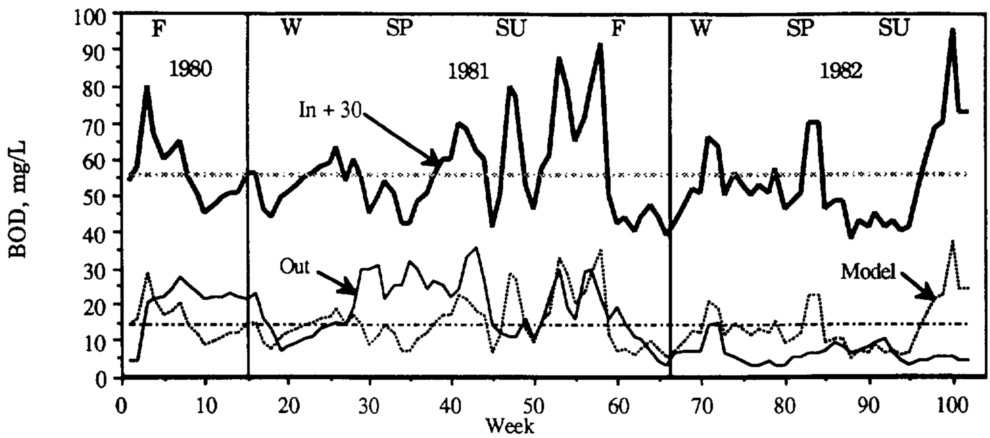

Figure 4. Time sequences of inlet and effluent BOD at Arcata pilot 12. Input has been shifted for clarity.

STOCHASTIC PROCESSES

Stochastic effects are a large part of treatment wetland performance. There are many causes, such as short term dynamics; input variations in flow and concentration; meteorological events of rain, drought, and heat waves; and biological influences due to algae, insects, fish, birds and animals. The result is a large degree of "chatter" about the mean performance, as illustrated in Figure 5. In this instance, there appears to be I/O tracking of the seasonal trend, but the daily measurements occupy a wide band about the mean.

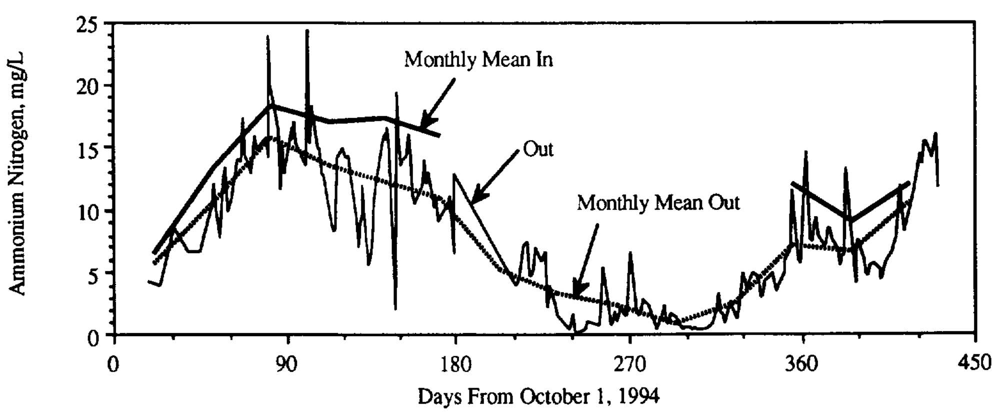

Figure 5. Columbia, MO effluent ammonium nitrogen time sequence.

In addition to the mean behavior described by the equations given above, measures of the variance about this mean are required. The frequency distributions of inlet and outlet concentrations provide this additional description. Phosphorus data from Listowel, ONT (Herskowitz, 1986) illustrate typical distributions (Fig. 6). The deterministic equations relate the mean values of the two distributions (k = 12.1 m/yr, $C^* \approx 0.0$ mg/L), but other points on the two curves are not so related. Current regulatory requirements in the USA dictate a maximum monthly value, other countries place a maximum on a given percentile, typically the 80th or 90th. Design must acknowledge regulatory requirements in most cases, and so must account for stochastic as well as deterministic effects. Where seasonal patterns are known to be significant, the design equations may be applied on that seasonal basis, but random variability still remains. Design can include this chatter, if the design target is adjusted downward by approximately a factor of 2.0 to meet a monthly maximum cap.

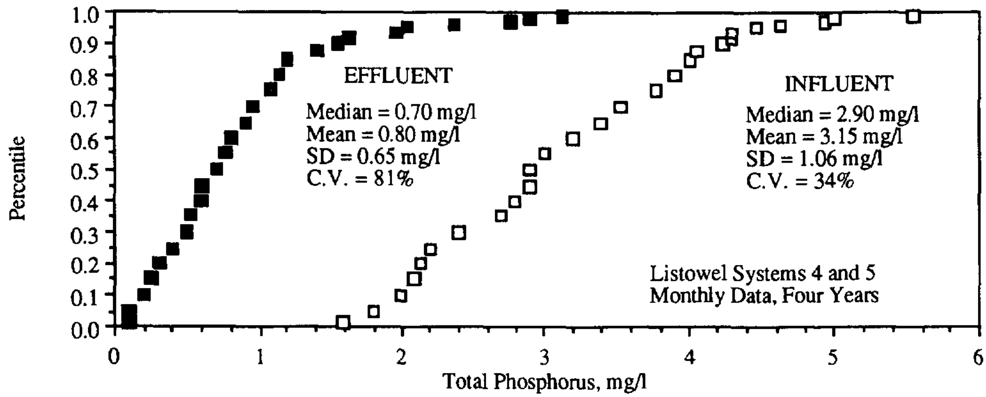

Figure 6. I/O probability distributions for TP at Listowel.

CLOSURE

The current treatment wetland design models are very simplistic. Some parameters, often thought to be constants, are in fact strongly dependent on operating conditions of flow and depth. Indeed, the very form of the equations is sensitive to the water balance. The recognition of non-zero wetland background concentrations provides a measure of relief from these variable "constants." Practitioners need to be aware of these interdependencies, in order to avoid over- and under-designs. There are now significant data collections that may be used to calibrate design models, which should be used in the design process. Current design equations describe only the deterministic component of wetland behavior, and hence must be accompanied by appropriate descriptions of stochastic behavior. It may be anticipated that more data, and Monte Carlo modeling, will improve the technology in this regard in the future.

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